

# Response of a New Soil Water Sensor to Variable Soil, Water Content, and Temperature

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## ABSTRACT

The success of time domain reflectometry (TDR) has led to the development of other instruments that use the soil dielectric constant as the basis for determining volumetric soil water content. An example is the Water Content Reflectometer (WCR; Campbell Scientific, Logan, UT), which is much less expensive than TDR and is used widely, although little has been published concerning its applicability to soil water content monitoring.<sup>1</sup> The primary objectives of this study were to determine the WCR soil water calibration for different soils and to investigate how it is affected by changing temperature. We found the individual sensors to be very precise ( $CV \leq 0.05$ ) under the controlled laboratory conditions of this study. Variability among sensors, determined in air and ethanol, indicated significant ( $\alpha = 0.05$ ) sensor differences that were largely accounted for with a simple additive correction. Sensor soil water calibration was investigated in four soils under varying water contents across a 40°C temperature range. We found that (i) soil water calibration was significantly ( $\alpha = 0.05$ ) different for each soil tested, (ii) there was a significant ( $\alpha = 0.05$ ) temperature response for all soils, and (iii) the effect of temperature varied with soil water content and soil type. Both the soil type and temperature sensitivities we observed were probably due to the relatively high electrical conductivity (EC) of the soils tested.

KNOWLEDGE OF soil water content ( $\theta$ ,  $m^3 m^{-3}$ ) is critical for determination of local energy and water balance, transport of applied chemicals to plants and groundwater, irrigation management, and precision farming. Several nondestructive methods have been devised to measure and monitor  $\theta$  including neutron thermalization (Greacen, 1981), electrical resistance (Colman and Hendrix, 1949; Spaans and Baker, 1992; Seyfried, 1993), TDR (Topp et al., 1980; Cassel et al., 1994), and electrical capacitance (Robinson and Dean, 1993; Nadler and Lapid, 1996).

In the past several years, TDR has been shown to provide accurate and precise measurements of  $\theta$  that are relatively insensitive to soil texture and chemistry variations (Zegelin et al., 1992). With TDR, the travel time of electric pulses traveling along a waveguide, which is directly related to the apparent soil dielectric constant ( $K_a$ ), is measured. Since the dielectric constant of water (80) is very much greater than that of air (1) or soil solids (3–5), the measured composite  $K_a$  is primarily a function of  $\theta$ . A fairly robust empirical calibration developed by Topp et al. (1980) is commonly used to compute  $\theta$  from  $K_a$ .

The high cost of TDR has led to the development of alternative means of using  $K_a$  to measure  $\theta$ . The use of soil capacitance to determine  $K_a$  was explored by

Thomas (1966) and later developed by Dean et al. (1987), whose work has led to commercial soil water measuring instruments (Evelt and Steiner, 1995; Paltineanu and Starr, 1997). Readers are referred to those papers for a more complete description of the measurement principles. Briefly, the basis for the approach is that when a capacitor is subjected to an oscillating current, the resultant oscillation frequency is related to the capacitance of the circuit, with the oscillation frequency decreasing as the capacitance increases. The exact relationship is specific to the circuitry of the instrument (e.g., Dean et al., 1987). In general, the relationship between the capacitance ( $C$ ) and  $K_a$  is

$$C = gK_a \quad [1]$$

where  $g$  is a constant dependent on the spacing and geometry of the capacitor and both  $C$  and  $g$  are measured in farads (Dean et al., 1987). Thus, the measured oscillation frequency is related to the  $K_a$  such that  $K_a$  decreases with increasing frequency. Empirical calibrations are used to relate  $\theta$  to frequency because of uncertainty in the value of  $g$  and in the complex relationship between  $\theta$  and  $K_a$  (Whalley et al., 1992).

The WCR consists of a printed circuit board connected to two parallel, 30-cm-long, 0.32-cm-diam. stainless steel rods 3.2 cm apart that act as waveguides. The electronic components within the circuit board are encapsulated in epoxy at the head of the instrument and are configured as a bistable multivibrator. The output is a square wave with an amplitude of  $\pm 2.5$  V DC. The resultant oscillation frequency, which ranges from  $\approx 15$  to 45 MHz, is linearly scaled down to the order of kilohertz to be read by a data logger, which is how it is recorded.

When the WCR is installed, the waveguide and soil act as a capacitor. Soil between and along the length of the rods affects the capacitance, but the instruments are most sensitive to conditions immediately adjacent to the rods (Campbell Scientific, 1996). Changes in  $K_a$ , which are primarily due to changes in  $\theta$ , are recorded as changes in the oscillation frequency. Results are generally reported in terms of the wave period ( $P$ , ms), which is the inverse of the frequency, because it increases with  $\theta$ . Data can be collected in a continuous mode (or at any specified interval) and stored on a data logger. No expensive TDR unit is required and soil water content information can be collected at considerable cost savings.

Although the basic operation principles for the WCR are the same as those for other recently described capacitance soil water content sensors, there are at least two notable differences: (i) the mode of soil-sensor contact

<sup>1</sup> Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the author or USDA.

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and (ii) the pulse generation method. The WCR uses a waveguide approach similar to TDR, which is in direct contact with the soil and senses an integrated average along and between the waveguides. Most other capacitance probes (e.g., Dean et al., 1987; Evett and Steiner, 1995; Paltineanu and Starr, 1997) use a down-hole approach, like the neutron probe. The capacitance sensors are not in direct contact with the soil, and the sensing volume radiates out from the access tube at specified depth intervals (e.g., Paltineanu and Starr, 1997). The WCR measures the oscillation frequency of a generated square wave, which may contain harmonics that influence the effective measurement frequency, while most other capacitance sensors measure the frequency of a slower rise time pulse (e.g., sinusoidal) that minimizes complications arising from harmonics.

Soil is a physically and chemically heterogeneous and complex medium, and various field applications may introduce conditions unanticipated during instrument development. Ideally, WCR soil water calibrations would apply to a wide range of soils, as with the TDR. However, we know of no published soil water content calibration of the WCR except that provided by the manufacturer (Campbell Scientific, 1996). One objective of this study was to determine if the WCR calibration varied with different soils. The other objective was to investigate the response of the WCR to changes in temperature. This is always a question when electronic instrumentation is used in field studies and has been identified as a topic requiring further investigation (Paltineanu and Starr, 1997).

## MATERIALS AND METHODS

### Soils

Four soils were used. Summit was collected from the top 30 cm of a Lolalita sandy loam soil (coarse-loamy, mixed, nonacid, mesic Xeric Torriorthent). Sheep Creek was collected from the upper 30 cm of a Searla loam (loamy skeletal, mixed, frigid Calcic Argixeroll). Foothill was collected from the argillic horizon of a Larimer loam (fine loamy over sandy skeletal, mixed, mesic Ustollic Haplargid). These three soils are common at ongoing study sites. The fourth soil was construction sand. The Summit, Sheep Creek, and sand were used in a previous study of TDR calibration and application to frozen soil (Seyfried and Murdock, 1996).

These soils exhibit a range of properties (Table 1). Each was packed to a consistent but different bulk density, which was determined at the end of each measurement from knowledge of the oven-dry soil weight and the container volume (Table 1). Electrical conductivity of the saturated paste extract (Table 1) was measured for each of the soils according to Rhoades (1982).

**Table 1. Soil properties.**

| Soil        | Sand                | Clay | Bulk density       | Electrical conductivity |
|-------------|---------------------|------|--------------------|-------------------------|
|             | kg kg <sup>-1</sup> |      | kg m <sup>-3</sup> | S m <sup>-1</sup>       |
| Sheep Creek | 0.23                | 0.19 | 1300               | 0.774                   |
| Summit      | 0.69                | 0.05 | 1700               | 0.253                   |
| Foothill    | 0.31                | 0.29 | 1500               | 0.145                   |
| Sand        | 0.97                | <0.1 | 1520               | 0.0000568               |

## Experimental Procedures

All experiments were performed using six WCR sensors (all version 8221-07) purchased at two different times (three each time) and from two different manufacturing batches. The WCR measurements are reported in terms of  $P$  (ms) as it was scaled down for output to the data logger. Where temperature variations were required, the sensors were placed in a walk-in environmental chamber. Analysis of variance and regression analysis were performed using the SAS statistical analysis package (SAS Institute, 1990). In addition to measurements in soils at different  $\theta$ s, measurements were made in three media not encountered in the field (air, ethanol, and oven-dry soils) to test different aspects of sensor performance.

### Air Measurements

Measurements were made with each of the six sensors suspended simultaneously in air and subjected to temperatures ranging from  $-5$  to  $45^{\circ}\text{C}$ . This enabled us to establish the response of the electronics to temperature changes independent of potential media effects. This is an important test for any field instrument that may be subjected to a wide range of temperatures. In addition, it allowed us to evaluate differences among individual sensors.

### Ethanol Measurements

We placed all six sensors, in pairs, in 10.2-cm-i.d. polyvinyl chloride (PVC) tubing 33-cm-long filled with ethanol and measured the resultant  $P$ . This test was used to determine if differences among individual sensors observed in air, and hence at very low  $K_a$  persisted when placed in a relatively high  $K_a$  medium. A fluid (rather than soil) was used because it eliminates any variability that may arise from differential contact between the sensor rods and the soil. Ethanol was chosen over other commonly available liquids because it has a dielectric constant of  $\approx 18$  at  $25^{\circ}\text{C}$  (Bao et al., 1996), which is within the range of values commonly encountered in soils. For example, a  $K_a$  of 18 corresponds with a  $\theta$  of  $0.32 \text{ m}^3\text{m}^{-3}$  if the Topp equation (Topp et al., 1980) is used.

### Oven-Dry Soil Measurements

The soils used were oven dried at  $110^{\circ}\text{C}$  for 1 d and packed to bulk densities approximating those obtained during the soil water calibration experiments. Each soil was measured three times with each sensor so that there were 72 measurements ( $3 \text{ measurements} \times 4 \text{ soils} \times 6 \text{ sensors}$ ). This test was performed to determine if we could impose a common  $P$  value for all soils tested when  $\theta = 0.0 \text{ m}^3\text{m}^{-3}$ .

### Soil Water and Temperature Measurements

Soil water calibrations and temperature effects were determined using four  $\theta$ s measured at 5, 15, 25, 35, and  $45^{\circ}\text{C}$ . We used lower  $\theta$ s for the sandier soils (Table 2) because we wanted to test a reasonable range of  $\theta$ s for each soil and to avoid redistribution of water in the columns during the experiments.

**Table 2. The four target soil water contents used for each soil.**

| Soil        | Soil water content        |      |      |      |
|-------------|---------------------------|------|------|------|
|             | 1                         | 2    | 3    | 4    |
|             | $\text{m}^3\text{m}^{-3}$ |      |      |      |
| Sheep Creek | 0.1                       | 0.2  | 0.3  | 0.4  |
| Summit      | 0.05                      | 0.13 | 0.21 | 0.30 |
| Foothill    | 0.10                      | 0.20 | 0.30 | 0.40 |
| Sand        | 0.05                      | 0.12 | 0.19 | 0.25 |

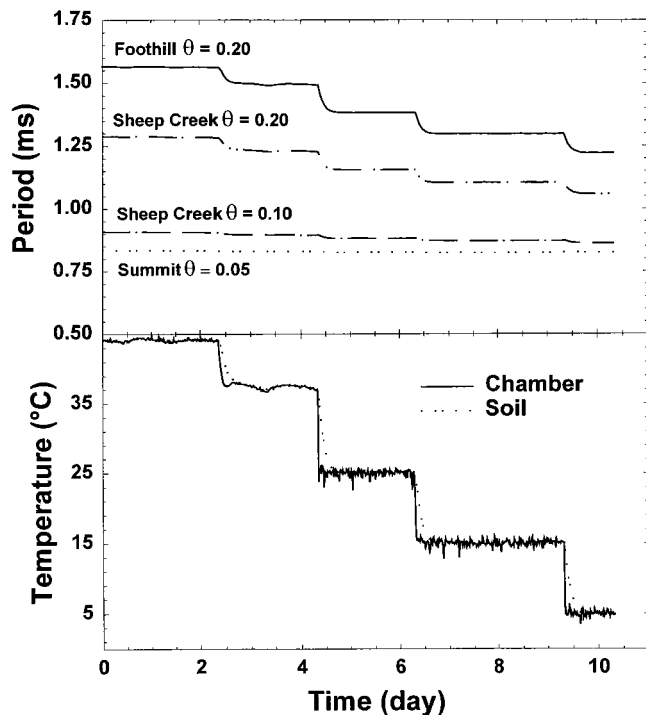


Fig. 1. Environmental chamber temperature, soil temperature, and period for four of the six samples measured during the eighth run. Only period readings collected when chamber and soil temperatures had equilibrated were used in subsequent analysis. Note that there were distinct temperature effects for two of the samples. The  $\theta$  values indicated are the target values, which were slightly different from what we actually measured.

The desired proportions of oven-dry soil and distilled water were thoroughly mixed and incrementally packed in 10.16-cm-i.d., 33-cm-long PVC tubing to a reproducible bulk density to produce a given soil- $\theta$  combination. The actual water content achieved was determined by weighing the entire contents of the PVC tube before and after oven drying overnight and multiplying by the measured bulk density. Each soil- $\theta$  combination was measured with three different randomly selected sensors, resulting in a total of 48 soil- $\theta$ -sensor combinations (i.e., 4 soils  $\times$  4  $\theta$ s  $\times$  3 replicates). These combinations were randomly assigned to one of eight different runs in the environmental chamber in which all six sensors were used. Air temperature was varied from 45 to 5°C in 10°C steps (Fig. 1). Temperatures were measured in air near the columns and in the soil near the center of the columns with calibrated thermocouples. Air and soil temperature and sensor-measured  $P$  were recorded at 20-min intervals. Data representing a given soil temperature were collected after the soil and air temperatures equilibrated.

## RESULTS AND DISCUSSION

### Response in Air

We observed a small, statistically significant ( $\alpha = 0.05$ ), linear effect of temperature on sensor response in air. Since the dielectric constant of air is not affected by temperature, these effects are indicative of the effects of temperature on instrument electronics. The coefficient of determination ( $r^2$ ) for linear regression of  $P$  on temperature ( $T$ , °C), was  $>0.98$  for all six sensors. The regression slope for each sensor was slightly negative

and very similar, ranging from  $-0.00050$  to  $-0.00057$  ms °C $^{-1}$ . Although there were significant ( $\alpha = 0.05$ ) differences among sensors, those differences had a negligible effect on sensor response (0.003 ms) for a 45°C temperature range, and we therefore used a single, average regression slope of  $-0.000533$  ms °C $^{-1}$  to describe the sensor temperature effect ( $S_T$ ) for all sensors tested.

Given this average sensor temperature response, a change of 45°C corresponds with a 0.024-ms period change. Using the standard calibration (Campbell Scientific, 1996) this corresponds with an apparent change in  $\theta$  of  $\approx 0.02$  m $^3$ m $^{-3}$ , which is negligible for many applications (especially those for which there is little temperature change). On the other hand, the temperature response is easily corrected since it is linear and practically uniform among sensors.

The regression constant ( $y$  intercept) values exhibited a statistically significant ( $\alpha = 0.05$ ) variation (0.026 ms) among sensors. This corresponds with  $\approx 0.02$  m $^3$ m $^{-3}$  differences among sensors in the same media. Since the regression slopes were, for practical purposes, uniform, these differences were unaffected by temperature. Hence, a constant additive sensor correction factor ( $S_C$ , ms), could be applied that accounted for differences among sensors across the entire temperature range.

Based on these results, we used the following combined temperature and sensor correction equation

$$P_C = (P_R + S_C) + (25 - T)S_T \quad [2]$$

where  $P_C$  (ms) is the sensor- and temperature-corrected period,  $P_R$  (ms) is the directly measured (raw) period, and  $S_C$ ,  $T$ , and  $S_T$  have been defined above. Application of Eq. [2] to the air measurements resulted in considerable reduction in response variability for all sensors combined. At 40°C, for example, the CV was reduced almost tenfold, from 1.34 to 0.14%.

### Response in Ethanol

Measurements from each individual sensor in ethanol were very precise, with a CV in all cases  $<0.05\%$ . Partly for this reason significant ( $\alpha = 0.05$ ) differences among individual sensors were observed. Considering all sensors combined, the average measured  $P$  was 1.209 ms with a standard deviation of 0.010. This value of  $P$  corresponds with a  $\theta$  of 0.34 m $^3$ m $^{-3}$  using the standard calibration supplied by the manufacturer (Campbell Scientific, 1996), which is in good agreement with the 0.32 m $^3$ m $^{-3}$  estimated previously. Correction of  $P_R$  with Eq. [2] using  $S_C$  values derived from air measurements resulted in more than a 50% reduction in variability among sensors. This corresponds with a standard deviation of  $<0.05$  m $^3$ m $^{-3}$  and a CV of 0.37%. The temperature correction was not evaluated because ethanol itself undergoes substantial changes in dielectric constant with temperature.

The practical implications of these results are twofold. First, the effect of temperature on instrument electronics is negligible for many applications in which temperature changes are small and easily corrected where necessary. Therefore, observed temperature responses using the WCR are mostly due to sensor-detected changes in



the medium (e.g., soil) rather than the sensor components. Second, individual sensors vary a small but not negligible amount. Since  $S_C$  values measured in air (low  $K_a$ ) effectively reduced intersensor variations in ethanol (high  $K_a$ ), those  $S_C$  values should provide effective correction of individual sensor variability in soil.

### Soil Water Calibration

In the remainder of this paper we refer to volumetric soil water content measured gravimetrically, which is used as the standard of comparison for calibration, as  $\theta_G$ . Also, the soil water content calculated from  $P_C$  (Eq. [2]) is referred to as  $\theta_C$ , the sensor and temperature corrected soil water content. We used calibration equations developed from the data collected for this project as well as two calibration equations provided by the manufacturer (Campbell Scientific, 1996), the standard and the high electrical conductivity calibrations.

### Oven-Dry Soil

There was no significant ( $\alpha = 0.05$ ) difference in  $P_C$  among oven-dry soils, which all had average measurements within 0.007 ms of the overall average of 0.760 ms. This is slightly (and significantly,  $\alpha = 0.05$ ) higher than that measured in air (0.745 ms), which is consistent with the small dielectric contribution of solid soil material. Application of Eq. [2] to correct for individual sensor differences resulted in a reduction in the combined standard deviation of 50% and a CV of 1.6%. This CV, though low relative to other instruments, is considerably greater than that measured either in air or ethanol (about five times), reflecting the effect of variable soil-sensor contact. Based on these results, we used a single, common  $P_C$  value at  $0.0 \text{ m}^3\text{m}^{-3}$  for calibration.

### Moist Soil

We found that the calibration relating  $P_C$  and  $\theta_G$  was significantly ( $\alpha = 0.05$ ) affected by soil type. At any given temperature, the measured  $P_C$  for a given  $\theta_G$  generally followed the order: Foothill > Sheep Creek > Summit > sand. Only the sand response agreed with the standard calibration (Fig. 2). At  $25^\circ\text{C}$  and  $\approx 0.25 \text{ m}^3\text{m}^{-3}$ , for example, the sand  $P_C$  was  $\approx 0.5 \text{ ms}$  less than that in the foothill soil (Fig. 2), which is about one-third of the entire  $P_C$  response range we observed.

These data demonstrate the importance of individual calibration for these soils. Using the standard calibration, the WCR  $\theta_C$  is  $0.965 \text{ m}^3\text{m}^{-3}$  ( $P_C = 1.8 \text{ ms}$ ) for a measured  $\theta_G$  of  $0.29 \text{ m}^3\text{m}^{-3}$ . This result contrasts with a previous study in which we showed that Sheep Creek, Summit, and sand could all be described with a single calibration curve using TDR (Seyfried and Murdock, 1996).

We used the following two-term polynomial equation forced through the previously determined zero point (0.760 ms) for the  $P_C$ - $\theta_G$  relationship for each soil

$$P_C = A + C_1 \theta_G + C_2 \theta_G^2 \quad [3]$$

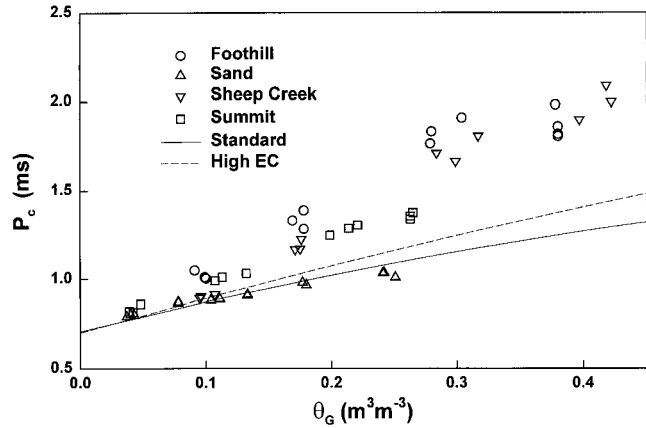


Fig. 2. Sensor and temperature corrected period ( $P_C$ ) determined using Eq. [2] related to  $\theta_G$  for all four soils at  $25^\circ\text{C}$ . There are three points from different runs for each soil- $\theta$  combination. The solid line represents the standard calibration supplied by the manufacturer. The dashed line the calibration for high EC ( $>0.3 \text{ S m}^{-1}$ ) soils.

where  $A$  is the zero point and  $C_1$  and  $C_2$  are empirical constants. The  $r^2$  for all soils ranged from 0.92 to 0.99 at  $25^\circ\text{C}$ , which is typical of other temperatures. The overall agreement between  $\theta_G$  and  $\theta_C$  calibrated by soil type was reasonably good ( $r^2 = 0.966$ ) with no major bias except that agreement tended to be worse as  $\theta_G$  increased (Fig. 3), which is consistent with the results from the oven-dry soils.

It has been recognized for some time that soil type can affect  $K_a$  and therefore estimates of  $\theta$  based on  $K_a$  (e.g., Wang and Schmugge, 1980; Dobson et al., 1985). The primary cause of differences among soils is usually attributed to the effects of solid-liquid interactions at the solid surface that restrict the rotational freedom of adsorbed water molecules. This water, sometimes termed *bound* water, is considered to have a dielectric constant much lower than that of free water (Dobson et al., 1985). In general, the amount of bound water may be expected to increase as the surface area of the soil increases. Therefore, for a given  $\theta_G$ , the more clay (i.e., greater the surface area), the more bound water, and the lower the  $K_a$ . Based solely on this reasoning, it was expected that the order of response among soils

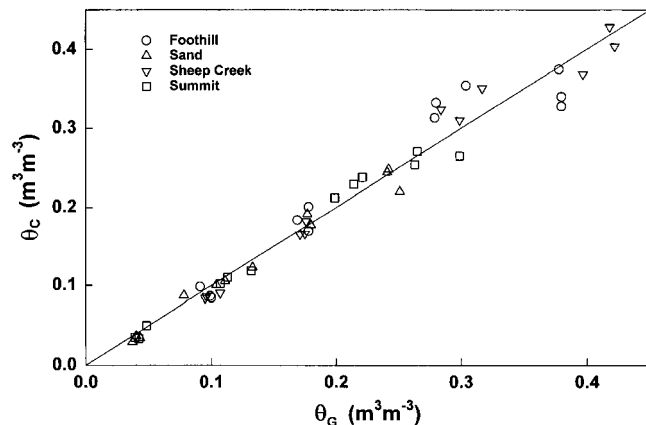


Fig. 3. Agreement between the  $\theta_C$  calculated with soil-specific calibrations using Eq. [3] and  $\theta_G$ . All data presented were collected at  $25^\circ\text{C}$ . The solid line represents perfect agreement.

would be exactly the reverse of what was observed, indicating that some other mechanism must be responsible for the observed differences in soils.

### Temperature Effects

Soil temperature had a significant ( $\alpha = 0.05$ ) effect on the measured  $P_C$  for all soils and water contents. The changes in  $P_C$  with temperature were linear in nearly all cases and much more pronounced at higher  $\theta_G$ s (Fig. 4a and 4b). With  $\theta_G = 0.30 \text{ m}^3\text{m}^{-3}$ , for example, the measured  $P_C$  for Sheep Creek soil increased from 1.45 to 2.00 ms at  $T$  increased from 5 to 45°C. Corresponding  $\theta_C$  changes using the soil-specific calibration (i.e., Eq. [3]) were from 0.249 to 0.404  $\text{m}^3\text{m}^{-3}$  (the standard calibration difference was four times greater). At the lower  $\theta_G$  of  $0.10 \text{ m}^3\text{m}^{-3}$ , the  $P_C$  change for Sheep Creek soil resulting from a 5 to 45°C temperature change was from 0.89 to 0.92 ms, which is equivalent to a  $\theta_C$  change of from 0.083 to 0.092  $\text{m}^3\text{m}^{-3}$  using the soil-specific calibration.

We used the slope of the  $P_C$ - $T$  relationship to quantify the effect of temperature on sensor response (Fig. 5). A temperature effect of 0 for a given  $\theta_G$  indicates that the sensor reading did not change as soil temperature changed from 45 to 5°C. We found that, within soils, the temperature effect increased in absolute value with  $\theta_G$ . At relatively small  $\theta_G$ s the temperature effect was

small for all soils tested, generally resulting in a 0.02 to 0.03  $\text{m}^3\text{m}^{-3}$  change over the 40°C temperature change. In addition, these small effects were fairly well described with the temperature correction supplied by the manufacturer (Campbell Scientific, 1996). With increases in  $\theta_G$ , however, there was a general divergence of temperature effect among soils. It is clear that temperature effects on sensor response are soil specific and cannot be accounted for with a single empirical correction factor.

Since the measurements presented are temperature corrected and the effects are soil specific, the measured values reflect soil properties rather than instrumental artifact. Some degree of temperature effect was anticipated strictly on the basis of the effect of temperature on the dielectric constant of water ( $\epsilon_w$ ), which is

$$\epsilon_w = 78.54[1 - 4.58 \times 10^{-3}(T - 25) + 1.19 \times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3] \quad [4]$$

(Weast, 1986). According to Eq. [4],  $\epsilon_w$  decreases from 86.12 to 71.7°C as the temperature increases from 5 to at 45°C. Thus,  $K_a$  and therefore  $P$  are expected to decrease with increasing temperature.

The magnitude of this decrease in a soil system can be calculated by incorporating Eq. [4] into dielectric mixing model equations (e.g., Roth et al., 1990; Pepin et al., 1995; Seyfried and Murdock, 1996). Pepin et al. (1995), working with sand, used the following mixing model equation attributed to Birchak et al. (1974)

$$K_a^\beta = V_w \epsilon_w(T)^\beta + V_m \epsilon_m^\beta + V_a \epsilon_a^\beta \quad [5]$$

where  $\beta$  is an empirical shape factor,  $\epsilon$  refers to the dielectric constant,  $V$  to the volumetric fraction of a given constituent, and the subscripts  $w$ ,  $m$ , and  $a$  refer to liquid water, solid material, and air constituents, respectively. Pepin et al. (1995) showed that, in sand, a combination of Eq. [4] and [5] effectively described temperature effects on  $K_a$ .

Following this approach, we used the following values taken from the literature (e.g., Dasberg and Hopmans, 1992):  $\epsilon_m = 3.9$  and  $\epsilon_a = 1.0$ , and a  $\beta = 0.515$  to calculate the expected effects of  $T$  on  $\theta$  due to changing  $\epsilon_w$  for sand. If  $\theta_G = 0.10 \text{ m}^3\text{m}^{-3}$ , a change in  $T$  from 5 to 45°C

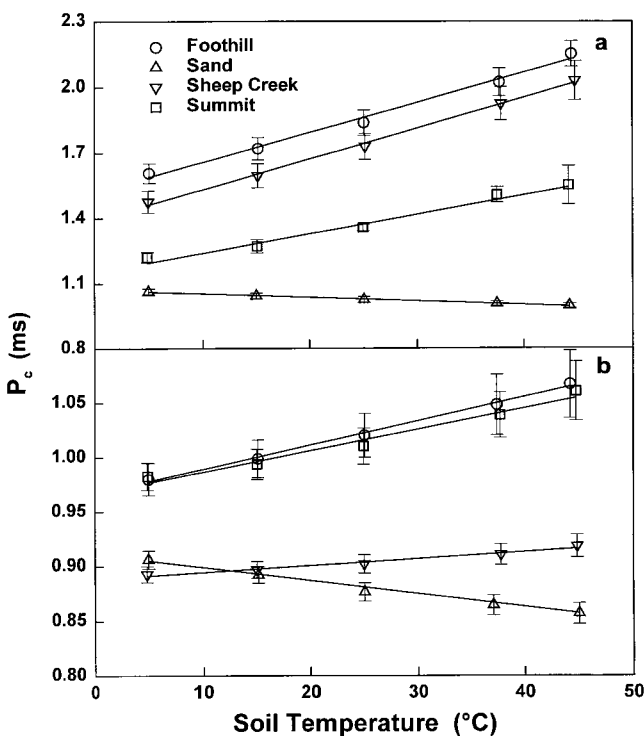


Fig. 4. Effect of temperature on WCR response (a) for soil water contents about  $0.30 \text{ m}^3\text{m}^{-3}$  (actually  $0.29 \text{ m}^3\text{m}^{-3}$  for Foothill,  $0.24 \text{ m}^3\text{m}^{-3}$  for Sand,  $0.30 \text{ m}^3\text{m}^{-3}$  for Sheep Creek, and  $0.28 \text{ m}^3\text{m}^{-3}$  for Summit) and (b) for soil water contents  $\approx 0.10 \text{ m}^3\text{m}^{-3}$  (actually  $0.10$  for all soils except Summit, which was  $0.12 \text{ m}^3\text{m}^{-3}$ ). Lines are the best fit linear regression. Each point is an average of the three replications with the error bars representing one standard deviation. Note the difference in y-axis scale between parts a and b.

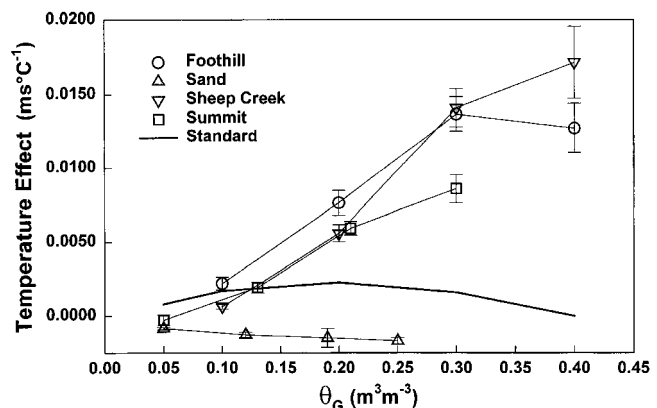


Fig. 5. Variation in temperature effect for the four soils with different  $\theta$  relative to the standard temperature correction provided by the manufacturer. Error bars represent the standard error for each point presented.

results in a calculated apparent change in  $\theta$  of  $-0.01 \text{ m}^3\text{m}^{-3}$ , which compares with a change of  $-0.04 \text{ m}^3\text{m}^{-3}$  measured with the WCR using the standard calibration. Similarly, for  $\theta_G = 0.25 \text{ m}^3\text{m}^{-3}$ , the effect of dielectric constant alone resulted in a  $-0.03 \text{ m}^3\text{m}^{-3}$  change as compared with a  $-0.07 \text{ m}^3\text{m}^{-3}$  change measured with the WCR. The values we calculated were very close to those measured by Persson and Berndtsson (1998) with TDR in sand. Thus, for the sand, the magnitude of effects of temperature on the WCR are slightly greater than those based on  $\epsilon_w$  calculated using Eq. [4] and [5].

The response of the other three soils to temperature was very different from the sand or that calculated from Eq. [4] and [5]. Most obviously, the temperature effect was strongly positive for those soils (Fig. 5). It was also of much greater magnitude. It has been noted that the effect of  $T$  on  $K_a$  measured with TDR may be less negative or even positive in soil with high clay content (Pepin et al., 1995; Persson and Berndtsson, 1998). This effect has been speculated to be due to a liberation of bound water as  $T$  increases. The magnitude of the temperature response of the WCR appears to be greater than that for TDR given the rather dramatic responses we have observed.

### Electrical Conductivity Effects

The sensitivity of the WCR sensors to EC may explain both the need for soil-specific soil water calibration and the relatively strong temperature response. The manufacturer notes that alternative calibration is required for the sensors when the soil solution EC is  $>0.1 \text{ S m}^{-1}$  (Campbell Scientific, 1996). Three of the soils studied, Sheep Creek, Summit, and Foothill, had soil solution ECs  $>0.1 \text{ S m}^{-1}$  (Table 1). The calibration for the low EC sand matched the standard calibration fairly closely (Fig. 2). However, for the high EC soils, no single calibration was appropriate and an alternative calibration supplied by the manufacturer for high EC ( $0.3 \text{ S m}^{-1}$ ) soils, which might have been appropriate for the Summit and Foothill soils, was not close to that observed (Fig. 2).

The EC of aqueous solutions (Fenn, 1987) and soils (Persson and Berndtsson, 1998) is strongly dependent on temperature, increasing by a factor of  $\approx 0.02$  for each degree C increase. It has also been documented that bulk soil EC tends to increase with  $\theta$  (Rhoades et al., 1989). Therefore, the observed sensitivity of  $P$  to temperature and the observed sensitivity of the temperature effect to  $\theta$  may also be attributed to EC. The sand, which exhibited minimal temperature response and fit the standard calibration, had a very low EC.

Although temperature effects and sensitivity to soil type have been noted for TDR, the effects appear to be much greater with the WCR. For example, previous study of the Sheep Creek, Summit, and sand soils indicated that a single soil water calibration was appropriate for all three soils (Seyfried and Murdock, 1996). The contrast between WCR and TDR is probably due to differences in measurement frequency. Although both techniques are based on  $K_a$ , the WCR works at frequencies between 15 and 45 MHz, while the effective fre-

quency for TDR appears to be much greater (Heimo-vaara et al., 1996). Campbell (1990) demonstrated that the dielectric behavior of soils is dominated by ionic conductivity at frequencies between 1 and 50 MHz and that  $K_a$  increased with temperature at lower measurement frequencies in that range. He concluded that sensitivity to EC even for relatively low EC soils ( $<0.1 \text{ dS m}^{-1}$ ) resulted in high sensitivity to soil type for measurements made within the 1- to 50-MHz range. Previous studies have demonstrated high sensitivity to soil type when using low ( $<30 \text{ MHz}$ ) frequencies (Gardner et al., 1991).

### CONCLUSIONS

We found that individual WCR sensors are very precise. The CV for a given sensor with 10 to 15 readings was below 0.05%, resulting in an almost imperceptible noise level. We also observed a significant degree of variability in response among different sensors, resulting in a response range corresponding to  $\approx 0.02 \text{ m}^3\text{m}^{-3}$ . This variation was constant across media and temperature, so that a simple additive correction factor based on measurements made in air could be effectively applied. There was also a slight effect of temperature on the sensor response in air, which can be ignored for many purposes but is also relatively easily corrected.

The soil water calibration for each of the four soils we tested was identical when the soil water content was zero. However, as soil water content increased, the calibration for each soil diverged significantly so that each soil required a separate calibration curve to relate  $\theta$  and  $P$ . The standard (manufacturer-provided) calibration agreed reasonably well only with the sand.

The WCR sensor's response was significantly affected by temperature for all soils tested. This effect increased in absolute value with  $\theta$ . For the sand, the temperature effect was negative, while for the other soils it was strongly positive, resulting in a large apparent  $\theta$  change across a  $40^\circ\text{C}$  temperature change. The effect of temperature on sensor response was also significantly different for each soil. Thus, accurate application of the WCR sensor requires a knowledge of the temperature as well as a soil-specific water content and temperature calibration. The standard calibrations supplied by the manufacturers apply fairly well to the sand but resulted in gross errors for the other soils.

Three of the four soils tested had relatively high soil solution ECs. This is the probable explanation for both the instrument insensitivity to soil type and temperature. Soil solution EC varies with soil and temperature. The sand soil, which had a very low EC, was slightly temperature sensitive and fit the standard calibration reasonably well.

Based on these findings, conditions characterized by low  $\theta$ , low bulk soil EC, and low temperature variation are optimal for using across-soil type calibrations and standard temperature corrections. Deviations from those conditions tend to require more soil-specific approaches.

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